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スロット塗布理論解析

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1. Abstract

Precise, rapid coating two layers simultaneously with a dual slot die is an established technology (e.g. Ishiwata et al. 1971, Sartor et al. 1996). However, interlayer diffusion can be deleterious; interlayer mixing by microvortices disruptive. Barring nonuniformities of unacceptable magnitude can be produced by back-up roll runout, feed pump ripple, air pressure ("vacuum") fluctuations, and substrate transport cogging that are impracticable to eliminate. Steady-state modeling by computational fluid mechanics reveals mixing, and is the precursor to frequency response analysis, an aid to understanding the nonuniformities and to designing active control to reduce them, as we reported about single-layer slot die coating at ISCST 2004. Here we report subsequent research on two-layer coating.

2. Interlayer treatment

A key issue is interdiffusion in the interlayer zone, which is not an interface (cf. Taylor & Hrymak 1997) yet has been approximated as one, though devoid of interfacial tension (e.g. Scanlan 1990, Cohen 1993, Musson 2001).

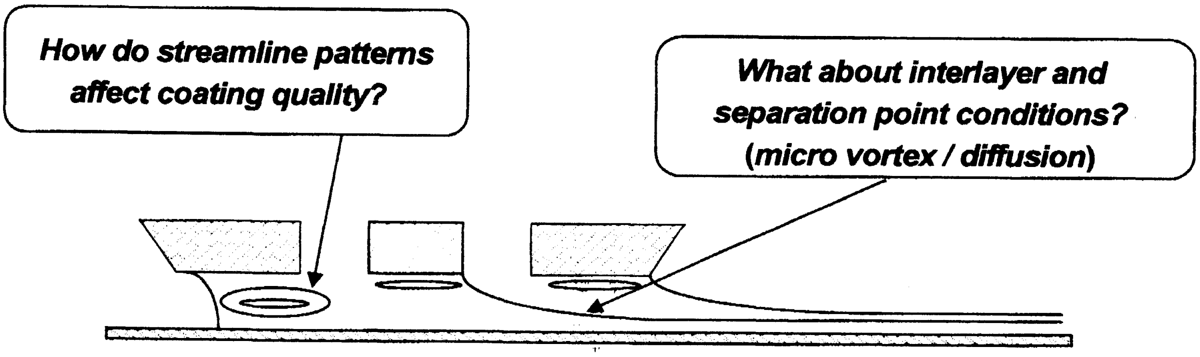


Fig. 1 Key issues in quality of two-layer slot coating.

Instead, we proposed a continuous interlayer zone model using a concentration variable. We have a fixed spatial domain, and model the fluid-fluid interfaces by assuming that the domain is occupied by two miscible fluids, A and B, with densities ρ_A and ρ_B and viscosities μ_A and μ_B. By using an interface variable c, it serves as a marker identifying fluid A and B with the definition,

$$C = \{1 \text{ for Fluid A and 0 for Fluid B}\} \tag{1}$$

The interface between the two fluids is approximated to be at c=0.5. In this context, ρ and μ are defined as

$$\rho = c\rho_A + (1-c)\rho_B\ ,\quad \mu = c\mu_A + (1-c)\mu_B \tag{2}$$

3. Flow and transport model and method of solving the equations

So we solved a convective-diffusion equation system eq.3, along with the usual Navier-Stokes system with a continuity equation eq.4 and elliptic equations of mesh generation, for steady-state regimes, and linearizations for imposed small sinusoidal disturbances.

$$\dot{c} + (\underline{u} - \dot{X}) \cdot \nabla c - \nabla \cdot (\frac{1}{Pe} \nabla c) = 0 \tag{3}$$

Time derivatives d /dt at fixed location were transformed to time derivatives at fixed isoparamtric coordinates, denoted by over-dot. Where c represents the quantity being transported concentration, and *Pe* shows the Peclet number.

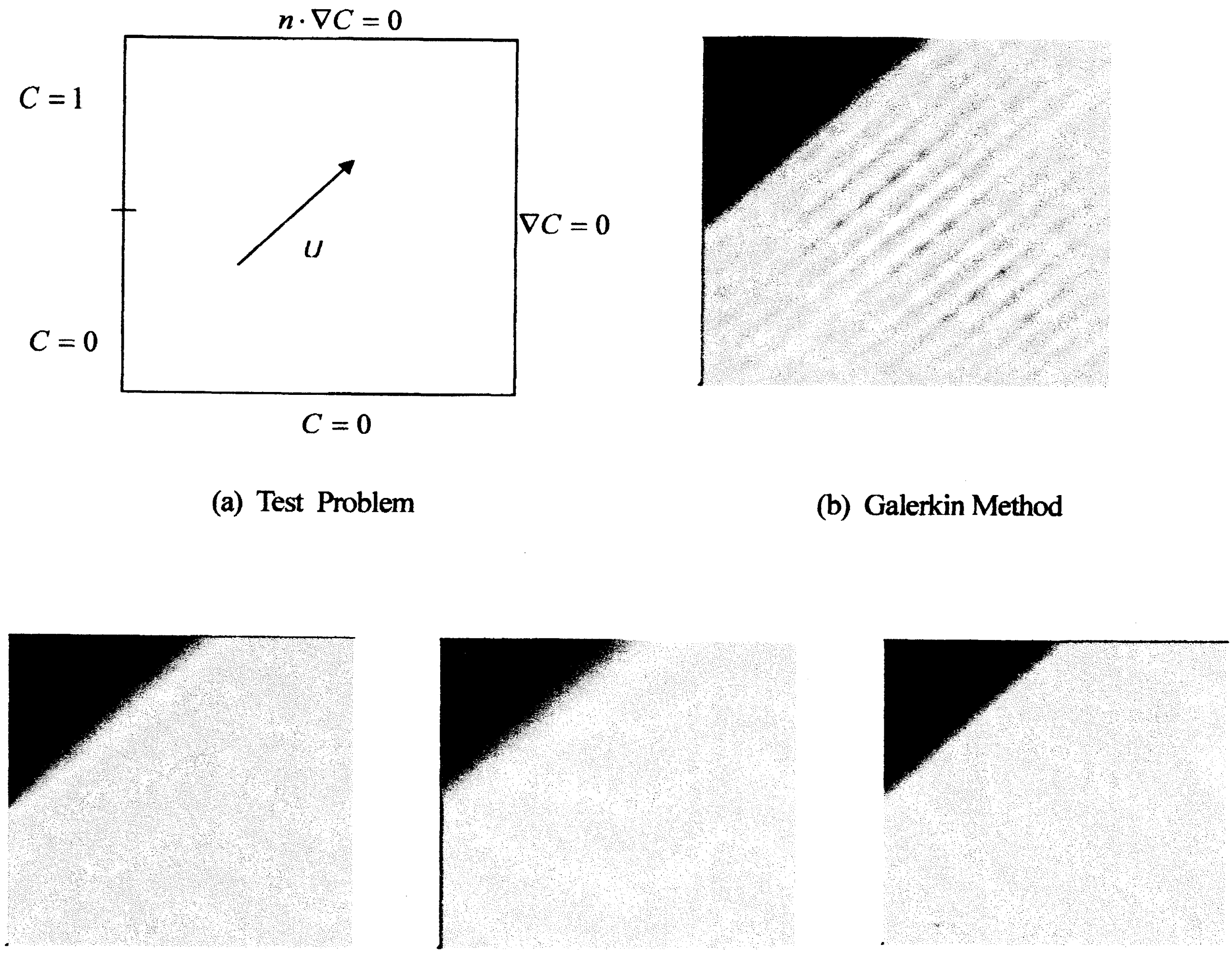
$$\begin{aligned} &\mathrm{Re}\,\dot{\underline{u}} + \mathrm{Re}(\underline{u} - \underline{\dot{X}}) \bullet \nabla \underline{u} = \nabla \bullet \underline{\underline{T}} + St\,\underline{f} \\ &\nabla \bullet \underline{u} = 0 \end{aligned} \tag{4}$$

Where u is the velocity vector and T is the total stress tensor in units of Ur and Lr/μUr respectively; Ur and Lr are the characteristic flow velocity, here web speed, and length, here the minimum gap. The Reynolds number is defined by Re=ρUrLr/μ. The Stokes number is defined by St≡ ρ gLr2/ μ Ur. And the unit of time t is Lr/Ur. The stress tensor is defined by

$$\underline{\underline{T}} = -p\underline{\underline{I}} + \left[(\nabla \underline{u}) + (\nabla \underline{u})^T\right] \tag{5}$$

The dimensionless pressure, p, is in units of Lr/μUr.

We employed the Galerkin Finite Element Method for the Navier-Stokes system and, to avoid extraneous wiggles associated with high local Peclet number, the Streamline Upwind Petrov-Galerkin technique for the convective-diffusion system along with the separating streamline. The separation point on the die's mid-lip was assigned the arithmetic mean concentration between the layers and on each side of the separating streamline an adaptively graded mesh was individually generated that amply resolved the interlayer diffusion zone. The sequence of alternatives tested is shown in Fig. 2.



(a) Test Problem

(b) Galerkin Method

(c) SUPG

(d) Galerkin Least Square

(e) SUPG + Adaptive Mesh

Fig.2 The sequence of alternatives tested. Conditions: 961(31 x 31) Quadratic Basis Functions, Peclet Number, 10^5. The separation point is located at intersection of C=0 and C=1 in Fig. 2(a).

4. Analysis of steady states and frequency response

The steady-state results show that when the top layer invades the mid-gap region, its residence time in the turnaround flow there heightens interlayer diffusion; and that onset of microvortices there and in the top-layer feed slot can indeed greatly mix the layers. The frequency-response results illustrate how 2D flow fields make variation of thickness at outflow.

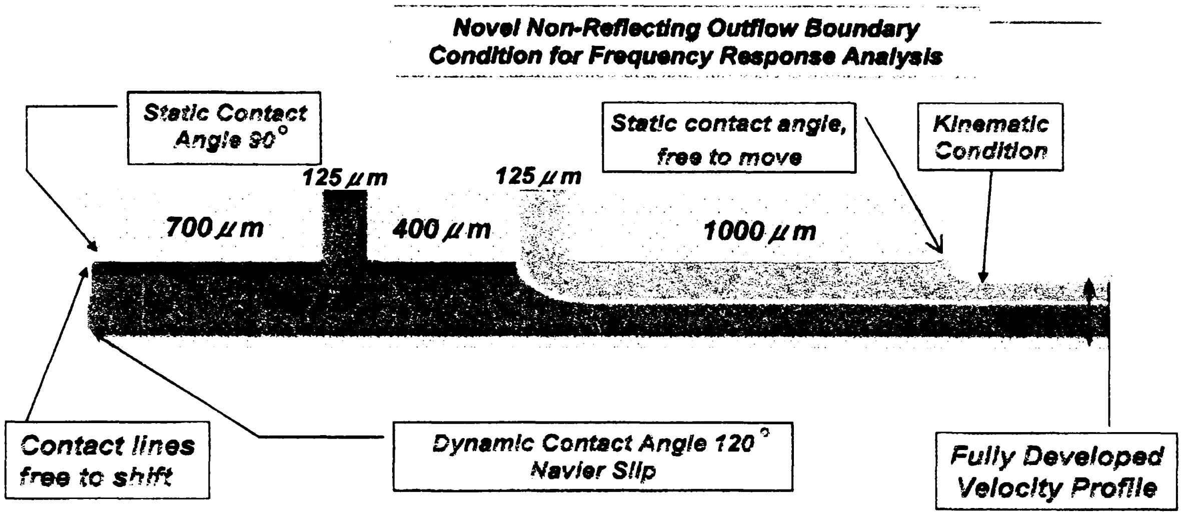


Fig. 3 Boundary conditions and a predicted steady state.

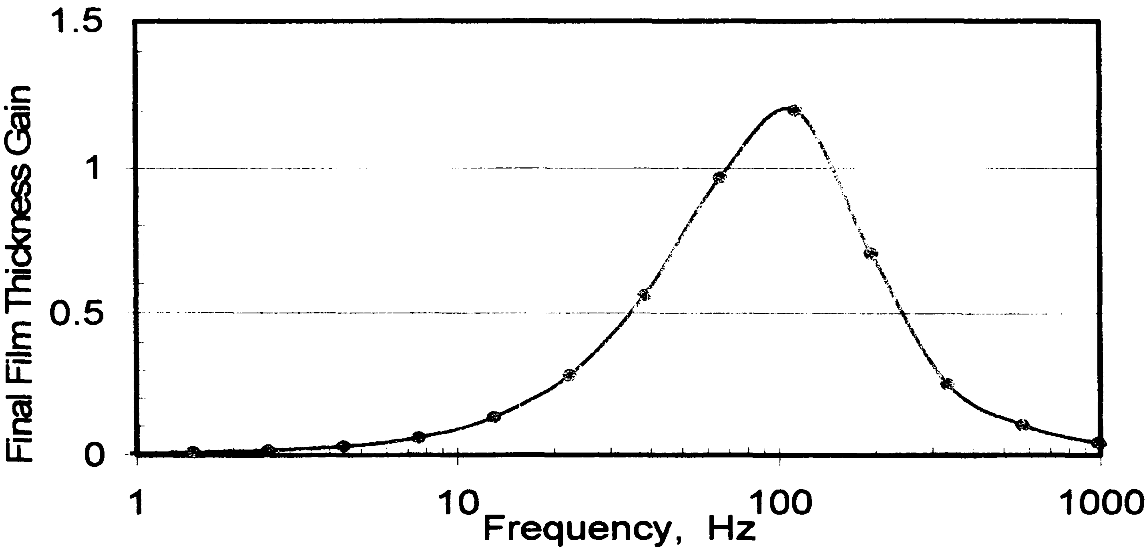


Fig. 4 Example of frequency response to coating gap oscillation. The web velocity is 50cm/s; both layers have the same density, 1.0 g/cc and the same viscosity, 0.5 P; at the top layer/air interfacial surface tension is 50dyn/cm; the vacuum pressure is 0 Pa; the film thickness ratio (upper to lower layer) is 0.5; the Peclet number is 10^5.

5. Active control

Besides frequency response to common disturbances, damping of dominant eigenmodes by active control was examined by solving the linear stability equation system without and with the equation of single-input sensing of a meniscus displacement and single-output control of flow rate. Fragmentary results indicate successful derivative control by choosing sensing point and gain on the basis of their effects on the damping coefficients of oscillatory normal modes, i.e. those whose eigenvalues have largest real parts.

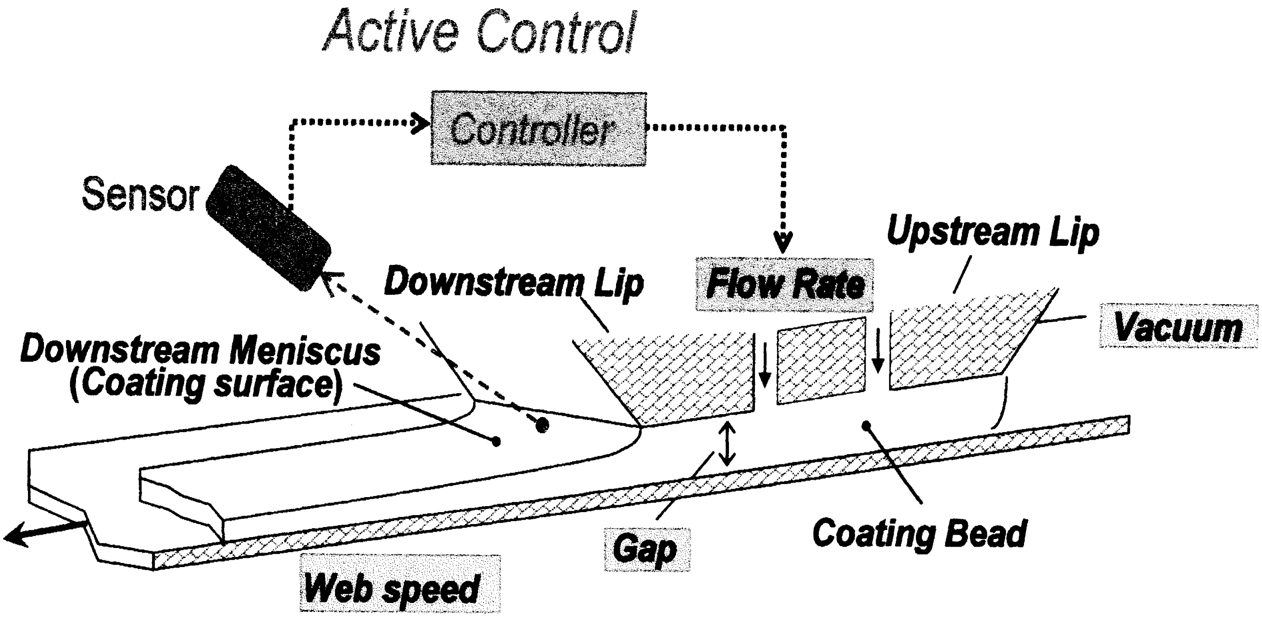


Fig. 5 Active control of two-layer slot coating flow

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